

Characterization of 3000 Volt MOS Controlled Thyristors

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Abstract

The MOS Controlled Thyristor (MCT) is a power thyristor which is turned on and off by a highly interdigitated surface array of MOSFET gates. The high-voltage diffusion-doped MCTs were developed by a three year contractual effort. These prototype MCTs have blocking voltages up to 3000 volts with a maximum controllable turn-off current density of 325 A/cm^2 in a 1 cm^2 active area die. A typical forward voltage drop is 2.5 V at 100 A with a 10/90% recovery time of 5 μs . Characterization of these devices was undertaken and has shown: surge turn-on capability of 15.5 kA in a 16 μs FWHM pulse; parallel operation of 3 devices at 300 A total current with less than 10% variation; and series operation of 3 devices at 5 kV, 150 A.

Introduction

The MOS Controlled Thyristor (MCT)^{1,2} is a power thyristor which is turned on and off by a highly interdigitated surface array of MOSFET gates. These switches require control energies equivalent to those required to charge the gate capacitance of a power MOSFET. Two types of p-MCTs have been investigated at ETDL. The first type being an epitaxially grown MCT³ which is rated for blocking voltages ranging from 500 V to 1000 V with peak controllable currents from 60 A to 120 A. This type of MCT is now in limited production at the Harris Corporation Mountaintop facility. The second type is a higher voltage 1 cm^2 active area diffusion-doped MCT⁴ developed under

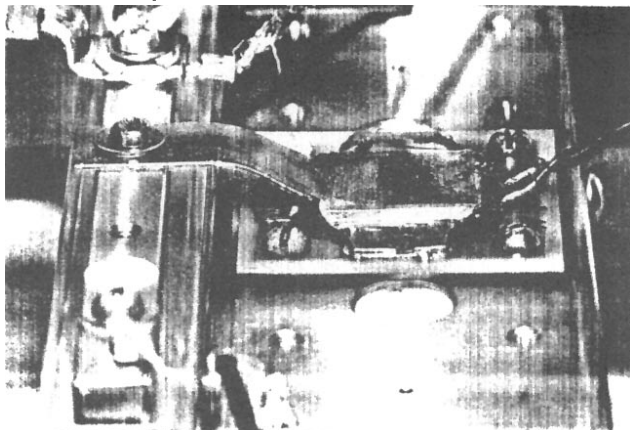


Figure 1. A high-voltage diffusion-doped MCT under test.

an ETDL contract.⁵ The prototype MCT devices (Figure 1) have blocking voltages up to 3000 V with a maximum controllable turn-off current density of 325 A/cm^2 and are the subject of this paper. Experimental results are presented which describe the switching characteristics of individual devices, surge (turn-on) capabilities, parallel array operation and series array operation up to 5000 V.

Discussion

Test circuit

The test circuit (Figure 2) consisted of a 300 μF capacitor bank in series with a resistive load and the device under test (DUT). Inductance was minimized to provide a device limited circuit. A snubber circuit consisting of a 0.1-0.47 μF capacitor (C_{sn}) in series with a charging diode was used for testing from 600 V to 1700 V to limit the rate of reapplication of voltage during turn-off. The turn-on current through the MCT is higher than the turn-off current because of the additional current of the snubber capacitor discharging through a limiting 40 ohm resistor (R_{sn}). Since the MCTs are p-type with the MOSFET control referenced to the anode, the MCTs were usually operated with the anode grounded and the cathode at negative potential. All device operating voltages mentioned in the paper are absolute voltages across the device under test.

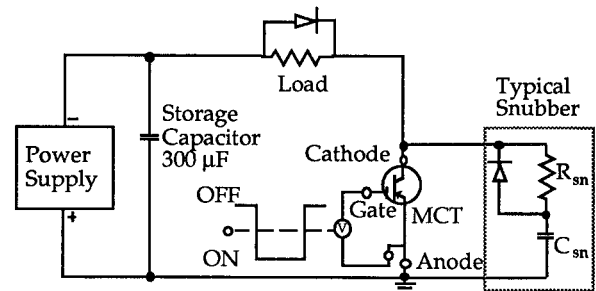


Figure 2. Basic circuit for characterizing MCTs for single, parallel, and series operation. The snubber capacitor, C_{sn} , is varied from 0.1 to 0.47 μF and the snubber resistor, R_{sn} , is 40 Ω . The load is varied from 3.3 to 16.2 Ω to limit peak controllable current.

High bandwidth Tektronix voltage probes and Pearson current transformers were used to monitor circuit voltage and currents. All waveforms were displayed and stored on a DSA 602 digitizing oscilloscope. The gate drivers³ for these experiments were self-contained, battery operated, and optically isolated for series

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operation. The gate drive was varied in amplitude for these tests from 7 V to 12 V for turn-off and -5 V to -10 V turn-on. Since the gate capacitance of these devices was approximately 32 nF, switching the MCTs on or off required less than 5 microjoules.

Characterization

The high-voltage diffusion-doped MCTs tested at ETDL were irradiated with electrons in doses of 0, 0.25, 0.5 and 1 MR. Irradiation of the devices increases the switching speed at the expense of increasing the forward voltage drop. Figure 3 shows the forward voltage drop and 10/90% current turn-off time at 100 A as a function of radiation dose for 16 devices.

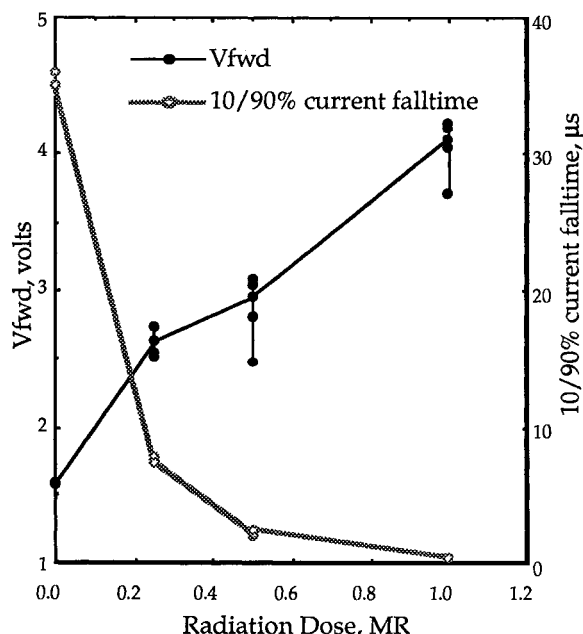


Figure 3. Forward voltage drop and current falltime as a function of radiation dose.

At 1.0 MR the average turn-off time of the devices is about 0.4 μ s but the forward voltage drop is about 4.1 V. At 0 MR the 10/90% turn-off time is about 35.5 μ s but the forward voltage drop is 1.6 V. The higher radiation doses also cause the devices to turn on faster. Faster switching devices have lower commutation losses/higher conduction losses, and conversely for slower switching devices. For a particular application an MCT can be tailored to minimize total operating losses.

Figure 4 shows the current and voltage waveforms of high voltage operation with a 10 Ω load of a diffusion-doped MCT irradiated with 0.5 MR dose of electrons. The voltage is 1520 volts with a peak current of 181 amps and a turn-off current of 150 amps. The 10/90% fall time of voltage (t_{fv}) was 0.29 μ s and the 10/90% current risetime (t_{rc}) was 0.28 μ s. The 10/90% voltage reapplication time was 13.1 μ s and the 10/90% fall of current (t_{fc}) was 8.2 μ s. There are however, two components of the current falltime and voltage recovery pulses; a fast component, and a slow component or long tail. The fast falltime of

the current (t_{fcfast}) is 0.22 μ s and the slow falltime of current is (t_{fclow}) is 16.5 μ s. The long tail is due to recombination in the wide base of the thyristor. The device can not return to its full blocking state until all the charge is recombined. The voltage reapplication time is a function of the carrier recombination time, snubber capacitor and the load, 13.1 μ s, rather than the RC time constant of the snubber capacitor and the load, which is 6.6 μ s. Test conducted at low voltage (≤ 600 V) without a snubber showed the same fast and slow components for the voltage reapplication waveform as observed on the current falltime waveform.

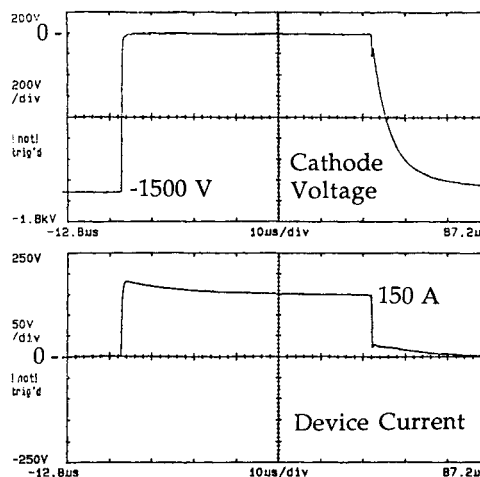


Figure 4. Voltage and Current Waveforms for High voltage operation.

Measurements were made of the falltime of current vs turn-off current for the same device operating over a current range of 22 A to 148 A into a 10 Ω load. The fast turn-off portion of the current, t_{fcfast} , is consistently less than 0.25 μ s. The long tail component of the current, t_{fclow} , increases from 14.8 μ s at 22 A up to 16.5 μ s at 149 amps. The increase in the long tail at higher currents is because there is more stored charge in the device undergoing recombination. A transition to the slow component of the current turn-off occurs at 14 % of the peak turn-off current.

Figures 5 and 6 show a comparison of current risetimes and voltage falltimes for an MCT irradiated with 0.25 MR. For the lower impedance loads, 3.3 and 6.6 ohms, operation was limited to voltages between 0 V and 600 V and no snubber was needed. At higher voltages a 0.3 μ F snubber was used. The device had faster current risetimes and voltage falltimes at higher voltages. The voltage falltime is determined by how fast the device changes from a blocking state to a conducting state and is independent of circuit impedance. After 500 volts the t_{fv} stays relatively constant at about 0.45 μ s. The current risetime is determined by the ratio of the circuit inductance to the load impedance, therefore at higher impedances faster risetimes are noted. The current risetime is strongly influenced by how fast current spreads in the device at higher voltages and the number of on FETs. Another factor that influences the current risetime is the L/R of the circuit and at higher impedances faster risetimes are noted.

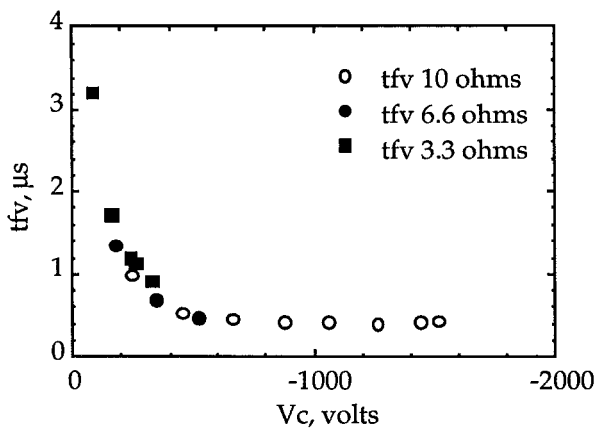


Figure 5. Comparison of voltage falltimes vs cathode voltage for different load impedances.

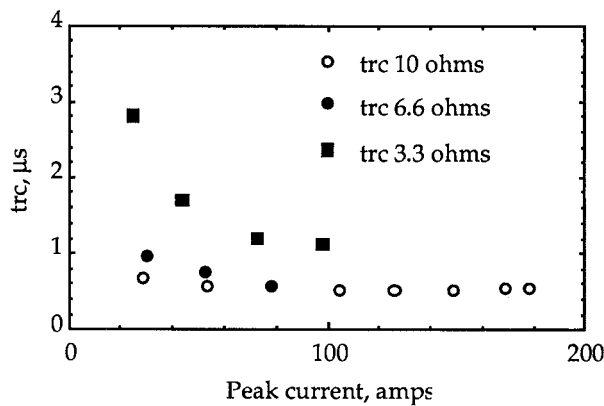


Figure 6 Comparison of current risetimes vs. peak current for different load impedances.

Parallel Operation

A study was conducted to evaluate current sharing when these devices are operated in parallel for high average power applications. Figure 7 is an example of three devices operating in parallel operation at 1500 volts, 292 amps total turn-off current.

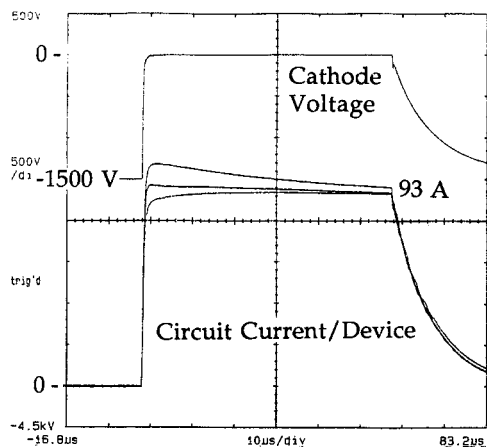


Figure 7. Parallel operation of 3 MCTs.

Initially current sharing is within 10%. As the current spreads in the devices the voltage drops equalize and the current variation between devices drop to 3%. Each device had an individual snubber consisting of a 0.1 μF capacitor, 20 ohm resistor and a parallel diode. In other tests a single snubber was used across the three devices consisting of a 0.3 μF capacitor, 40 ohm resistor and a diode. The individual snubbers are preferred because they limit the peak turn-on current and helps equalize dissipation per device.

Series Operation

Since there is always a limit to the amount of voltage any one device can handle, diffusion-doped MCTs were operated in a series configuration to increase the total controllable voltage. Three devices from the same wafer were operated in a series circuit with resistive load values of 20, 25, and 33 ohms. The stack was operated at 100 Hz with a 60 μs pulse width. In these tests turn-off current was limited to 150 amps for safe operation. Each device had a snubber circuit consisting of a 0.47 μF capacitor (chosen more for convenience than for optimal performance), a 40 ohm resistor and a parallel diode. A resistor divider consisting of three 100 k Ω resistors in series was used to equalize voltage division during the interpulse interval. Figure 8 shows the current and voltage waveforms of the stack operated at 5 kV, turning off 150 amps with a load of 33 ohms. The voltage falltime is 0.31 μs and the current risetime is 0.3 μs .

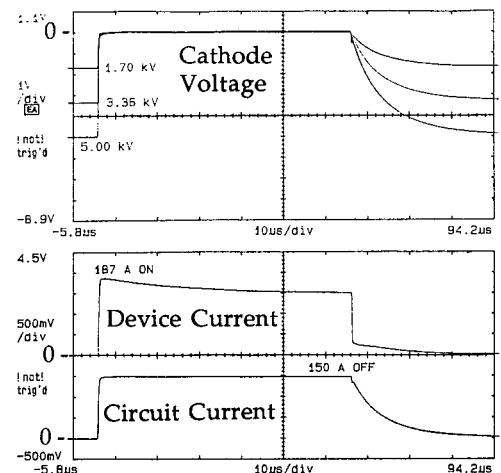


Figure 8. Series operation of 3 MCTs.

The reapplication of voltage time is 18.2 μs and the total falltime of current is 8.56 μs . The fast falltime of current is 0.23 μs and the slow falltime of current is 20.3 μs . The voltage division at turn-off is essentially equal. The difference in voltage sharing was less than 2% for both turn-on and turn-off. The peak power switched by the stack was 750 kW at an average power of 4.5 kW. The switching efficiency of the stack of MCTs is greater than 93% including snubber losses (the snubber capacitor was larger than necessary).

Surge Testing

Since the MCT has a highly interdigitated gate structure it has the capability to turn-on very high peak currents. In one case as shown on Figure 9, the MCT discharged a 120 μ F capacitor bank at 1720 volts into an ~ 0.1 ohm load producing 15.5 kA in a 15 μ s pulse (FWHM) with a current reversal, due to the slightly underdamped circuit, of 1900 amps. When the voltage reversal occurs the MCT conducts the high current in the reverse direction due to the presence of stored charge in the wide base. In another case, the MCT discharged a 300 μ F capacitor bank charged to 1600 volts producing a 10.7 kA current pulse in a 50 μ s pulse. The total energy switched in this single shot was 500 J with an estimated 21 J dissipated into the switch. In both cases the switching efficiency was over 95%. The surge testing is still very preliminary and the operational limits of the MCTs have not been determined.

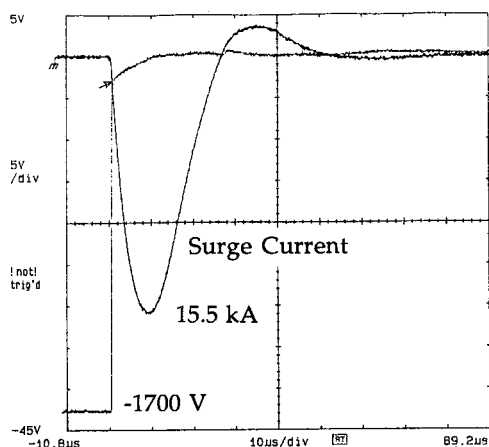


Figure 9. Surge turn on test of an MCT at 1720 V, 15.5 kA peak with a current reversal of 1.9 kA.

Summary

Although this new high-voltage diffusion-doped MCT is still in the development stage, experiments with these devices indicate that it has great potential for pulse power and high voltage switching applications. MCTs with breakdown voltages from 2000 V to 3000 V and peak controllable currents of 200 A were studied. The devices were operated from 1500 to 1700 V at safe peak controllable current of 150 A. The devices turned on in 0.4 μ s (10/90%) and turned off in 15 μ s (10/90%). The turn-off consists of two regions: a fast part which drops from 150 A to 20 A in about 300 ns, and a slow part which

decays to zero in 5-30 μ s. Higher irradiation, which decreases the carrier lifetime, increases the devices speed on turn-off but at the cost of increased forward voltage drops.

The devices were operated in a series stack up to 5 kV at 150 A, switching a peak power of 750 kW. Voltage division was within 2%. Parallel operation of three devices at 300 A was also investigated and current sharing at turn-off of the devices was within 3%. Investigation of the MCTs at high frequencies up to 50 kHz for inverter applications is in progress.⁶ Continuous operation was limited to 4.5 kW average power for most of the testing, except for the high frequency inverter testing where burst operation at 160 kW average was demonstrated.

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